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VISIBLE AND INFRARED OBSCURATION EFFECTS OF ICE FOG

MAY 1981

By

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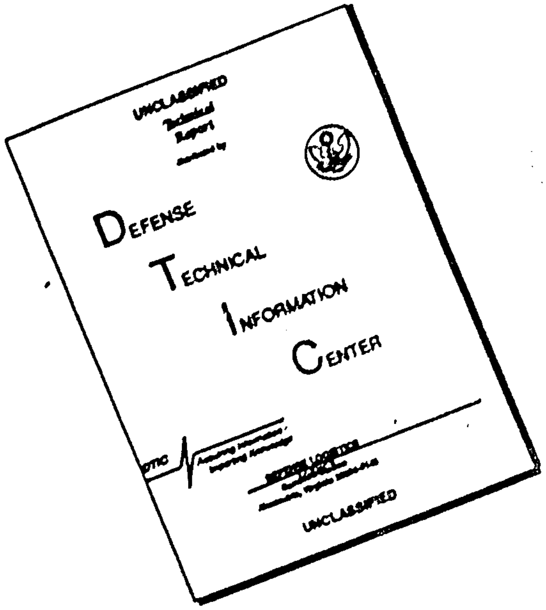

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20. ABSTRACT (cont)

Visible wavelengths are found to be less obscured than 1.06, 3.5 to 5.0, and 11.5 to 12.0 micrometers and more obscured than 3.0 and 8 to 11 micrometers.

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INTRODUCTION

Ice fog is a phenomenon which occurs when the ambient temperature goes below -30°C in urban areas around airfields and in other regions where there are human activities.[1] This phenomenon occurs more frequently and with greater density as the temperature decreases below -30°C. When water vapor is released into the atmosphere through combustion processes, vehicular activity, evaporation from open ponds, and other similar sources, it tends to condense into liquid water droplets. As these droplets freeze, ice fog is formed. Ice fog would very likely form on the battlefield if the temperature were below -30°C since vehicular activity and combustion processes would provide sources of water vapor. The presence of ice fog would seriously degrade the visibility and the utility of electro-optical devices.

ICE FOG CHARACTERISTICS

Robinson and Bell[2] found that ice fog forms in conditions of low temperatures, clear skies, and low windspeeds associated with polar continental air masses. Steep surface-based temperature inversions which develop under such conditions confine water vapor emitted near the surface to a shallow layer of air, in which the ice fog forms. The moisture tends to be uniformly distributed within the layer which is usually 50 to 100 meters deep and has a well-defined upper limit.

Visibility tends to be reduced to 100 to 200 meters; but in some cases, such as on major thoroughfares in Fairbanks, Alaska, it deteriorates to 15 to 20 meters.[3] At colder temperatures, the visibility tends to be less than when the temperature is near -30°C.

Visibilities in excess of 300 kilometers have been observed in the largely uninhabited regions of interior Alaska in the Arctic winter; however, at the same time ice fog has been observed in the cities and near the airports. Studies of conditions at Fairbanks have shown that ice fog is not very probable in temperatures between -30°C and -40°C, is probable in temperatures less than -40°C, and is nearly inevitable in temperatures colder than

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[1] T. Ohtake, 1970, "Studies on Ice Fog," UAG R-211, Geophysical Institute of the University of Alaska, Fairbanks, Alaska

[2] E. Robinson and G. B. Bell, Jr., 1956, "Low Level Temperature Structure Under Alaskan Ice Fog Conditions," Bulletin American Meteorological Society, 37:506-513

[3] AeResearch, Inc., 1975, "Baseline Ice Fog Visibility Study," AeResearch, Inc., College, Alaska

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-46°C.[4] The diurnal variation of ice fog occurrence is rather small;[5] however, ice fog does tend to occur somewhat more frequently during daylight hours in some locations. This tendency can be explained by the higher rate of human activity during the day.

The mechanism of ice fog formation is simply this:

1. Water vapor enters the atmosphere;

2. Droplets are formed as the water vapor condenses; and

3. The droplets freeze and form ice fog.

The droplets tend to freeze within a few seconds after formation.[1] Freezing takes place either through homogeneous nucleation or heterogeneous nucleation processes. Homogeneous nucleation is the formation of ice crystals from pure water and generally occurs at temperatures colder than -37°C. Heterogeneous nucleation is the process in which an ice crystal is formed when water freezes upon a minute particle of a foreign substance called an ice condensation nucleus. Ice fog seldom occurs at temperatures greater than -30°C because of the rarity of particles which are active ice condensation nuclei at warmer temperatures. Ice fog particles formed by homogeneous nucleation are usually slightly irregularly shaped solid particles with rudimentary crystal faces called "droxtals."[6] Heterogeneous nucleation usually results in crystals which are hexagons or prisms. The hexagons and prisms tend to be larger than the droxtals and occur less frequently at the colder temperatures where homogeneous nucleation is more prevalent. The diameters of the particles are usually between 2 and 15 micrometers with the mean value near 7 to 10 micrometers. The mean diameter of the particles decreases with decreasing temperature. While the concentration of ice fog particles varies with time and space, the size distribution has been found to remain constant if the source of water vapor does not change.[1] The size distribution is usually multimodal in urban areas where there are multiple sources of water vapor and unimodal at other locations.

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[4] V. J. Oliver and M. B. Oliver, 1949, "Ice Fogs in the Interior of Alaska," Bulletin American Meteorological Society, 30:23-26

[5] J. M. Mitchell Jr., 1958, "Visual Range in the Polar Regions with Particular Reference to the Alaskan Arctic," Polar Atmosphere Symposium Part I Meteorology Section, Pergmon Press, London

[1] T. Ohtake, 1970, "Studies on Ice Fog," UAG R-211, Geophysical Institute of the University of Alsaka, Fairbanks, Alaska

[6] W. C. Thuman and E. Robinson, 1954, "Studies of Alaskan Ice Fog Particles," Journal of Meteorology, 11:151-156

OPTICAL PROPERTIES OF ICE FOG

Visually, ice fog appears to be very similar to other types of fogs. However, the average size of ice fog particles is usually less than that of other types of fogs and favors greater optical scattering.[5] Thus, the visibility is less in ice fog than in other types of fogs for the equivalent liquid water content. An empirical relationship relating visual range, V_m, to liquid water content, w,[7] is:

$$V_m = \frac{1.3}{w} [3.2(\frac{w}{N})^{1/3} - 1.5\bar{d}] ,$$

where N = particle number density, and $\bar{d}$ = mean linear diameter. This formulation accounts for differing particle size distributions but does not relate to temperature or other environmental factors.

Two studies[8] [9] have been conducted which compared extinction at various wavelengths to results of Mie scattering calculations. These studies found that Mie calculations and experimental measurements agree within the limits of experimental error for wavelengths ranging from 0.63 to 3.4 micrometers. The measurements used in these studies were made at temperatures of -40°C or colder. At these temperatures, the ice fog particles which predominate are the small, almost spherical droxtals; while the larger, less nearly spherical prisms and hexagons are relatively few. The success of the Mie theory in predicting extinction in ice fog is assumed to be due to this predominance of nearly spherical particles. Based on these studies, the conclusion was that results of Mie scattering calculations may be used in deriving relationships between visible and infrared extinction.

MIE SCATTERING CALCULATIONS

To derive these relationships between extinction at visible wavelengths and that at 1.06, 3 to 5, and 8 to 12 micrometers, calculations were made by using

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[5] J. M. Mitchell Jr., 1958, "Visual Range in the Polar Regions with Particular Reference to the Alaskan Arctic," Polar Atmosphere Symposium Part I Meteorology Section, Pergmon Press, London

[7] T. Ohtake and P. J. Huffman, 1969, "Visual Range in Ice Fog," Journal of Applied Meteorology, 8:499-501

[8] H. W. O'Brien and M. Kumai, 1973, "Transmission of 2.0 to 3.4 Micron Infrared Radiation in Ice Fog," SR 189, Cold Regions Research and Engineering Laboratory, Hanover, NH (AD 766301)

[9] R. Munis and A. Delaney, 1972, "Measurements of Laser Extinction in Ice Fog for Design of SEV Pilotage System," RR 302, Cold Regions Research and Engineering Laboratory, Hanover, NH (AD 750114)

a general-purpose Mie scattering code as described by Shirkey et al.[10] The particle size distributions used are shown in figure 1 and are based on measurements made in the Fairbanks area as reported by Kumai and Russell.[11] Distribution 1 in figure 1 represents the ice fog crystals occurring at -39°C, while distribution 2 represents an occurrence at -41°C. The complex indices of refraction for ice which were used are shown in table 1[13] and are as tabulated by Paltridge and Platt.[12] Extinction coefficient calculations were made for both size distributions for various wavelengths and particle number densities.

The findings show that if the particle number densities were varied while the particle size distribution and the wavelengths were held constant the resulting infrared extinction coefficient, σ_{IR}, was very nearly a linear function of the visible extinction coefficient, σ_{VIS}. Slight differences were noticed between the linear relationship resulting from the two particle size distributions.

However, relatively large variations were noticed when the particle size distributions and number densities were fixed and the wavelength was varied over the ranges of 3 to 5 and 8 to 12 micrometers (table 1).

As a result, the conclusion was that a simple linear relationship of the form

$$\sigma_{IR} = C\,\sigma_{VIS}\,, \tag{1}$$

where C is a constant, would be suitable for λ = 1.06 micrometers but would not be particularly descriptive for the 3- to 5- and 8- to 12-micrometer regions. The more general form

$$\sigma_{IR} = f(\lambda)\sigma_{VIS}\,, \tag{2}$$

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[10]R. C. Shirkey et al, 1980, Single Scattering code AGAUSX: Theory, Applications, Comparisons, and Listing, ASL-TR-0062, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

[11]M. Kumai and J. D. Russell, 1969, "The Attenuation and Backscattering of Infrared Radiation by Ice Fog and Water Fog," RR 264, Cold Regions Research and Engineering Laboratory, Hanover, NH (AD 689447)

[13]W. M. Irvine and J. B. Pollack, 1968, "Infrared Optical Properties of Water and Ice Spheres," Icarus, 8:324-360

[12]G. W. Paltridge and C. M. R. Platt, 1976, Radiative Processes in Meteorology and Climatology, Elsevier Scientific Publishing Company, Amsterdam, the Netherlands

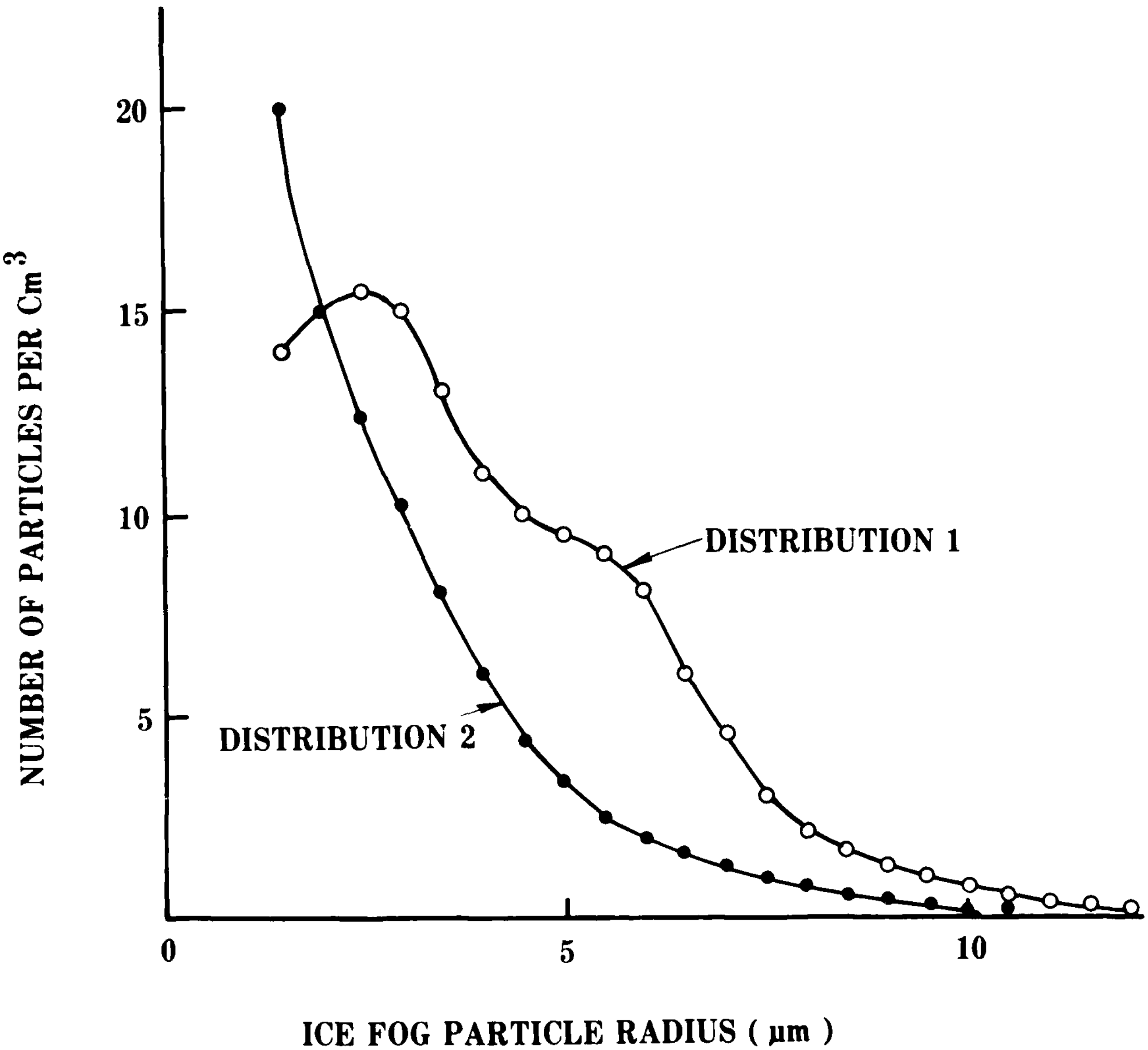

Figure 1. Ice fog particle size distributions.

TABLE 1. COMPLEX INDICES OF REFRACTION (PALTRIDGE AND PLATT, 1976), VOLUME EXTINCTION COEFFICIENTS, AND RATIO OF INFRARED AND VISIBLE EXTINCTION COEFFICIENTS FOR ICE FOG

Wavelengths (μm)	Index of Refraction (m)	(k)	Computed Extinction Coefficient (km^{-1}) Distribution 1 (140/cm³)	Distribution 2 (140/cm³)	$\left(\frac{\sigma_{IR}}{\sigma_{VIS}}\right)$
0.40	1.3	10^{-8}	20.38	13.18	
0.55	1.3	10^{-8}	20.64	13.43	
0.70	1.3	10^{-8}	20.83	13.56	
Mean 0.4-0.7			20.62	13.39	
1.06	1.3	2.5×10^{-6}	21.31	13.76	1.031
3.0	1.13	0.2273	20.42	12.90	.976
3.1	1.280	0.3252	21.96	14.23	1.064
3.2	1.557	0.1562	23.26	15.47	1.142
3.3	1.530	0.0625	23.70	15.93	1.170
3.4	1.490	0.0307	24.14	16.33	1.196
3.5	1.422	0.0163	24.43	16.83	1.221
3.6	1.395	0.0105	24.54	17.11	1.234
3.7	1.375	0.0093	24.79	17.29	1.246
3.8	1.356	0.0082	25.20	17.39	1.260
3.9	1.340	0.0104	25.65	17.37	1.270
4.0	1.327	0.0124	26.05	17.32	1.278
4.1	1.316	0.0150	26.39	17.25	1.284
4.2	1.307	0.0175	26.66	17.16	1.288
4.3	1.299	0.0218	26.80	17.02	1.286
4.4	1.288	0.0282	26.79	16.75	1.275
4.5	1.280	0.0330	26.70	16.50	1.263
4.6	1.272	0.0287	26.99	16.46	1.269
4.7	1.266	0.0215	27.43	16.52	1.282
4.8	1.258	0.0173	27.67	16.43	1.284
4.9	1.252	0.0147	27.75	16.27	1.280
Mean 3-5			25.37	16.42	1.226
8.0	1.219	0.0369	18.08	9.58	.797
8.5	1.217	0.0352	16.76	8.80	.735
9.0	1.210	0.0365	15.12	7.88	.660
9.5	1.192	0.0310	12.49	6.42	.543
10.0	1.152	0.0413	9.24	4.81	.404
10.5	1.192	0.0602	12.04	6.35	.530
11.0	1.290	0.0954	18.02	9.76	.802
11.5	1.393	0.1140	22.47	12.42	1.009
12.0	1.480	0.1200	25.19	14.13	1.139
Mean 8-12			16.60	8.91	.736

where $f(\lambda)$ is a polynomial in the wavelength, λ, was assumed for these regions. To find $f(\lambda)$ in equation (2), the quantity σ_{IR}/σ_{VIS} was computed for the two particle size distributions with fixed particle number density and for each wavelength. The visible extinction coefficient, σ_{VIS}, was taken to be the mean of that found for λ = 0.4, 0.55, and 0.7 micrometer. Then, the quantity $(\sigma_{IR}/\sigma_{VIS})$ was obtained by taking the average of σ_{IR}/σ_{VIS} for the two distributions at each wavelength. The results are tabulated in table 1 and also illustrated in figures 2 and 3. Sixth-order polynomials of the form

$$(\sigma_{IR}/\sigma_{VIS}) = f(\lambda) = \sum_{i=0}^{n} A(i)\lambda^{i}$$

gave sufficient accuracy. The coefficients, A(i), are given in table 2 for each of the wavelength regions with the resulting curves shown in figures 2 and 3. For λ = 1.06 micrometers, the constant C in equation (1) was found to be 1.034, giving

$$\sigma_{1.06} = 1.034\ \sigma_{VIS}\ .$$

CONCLUSIONS

Results of Mie scattering calculations have been used to derive relationships between the extinction coefficients, σ_λ, for visible and infrared wavelengths. These relationships are as follows:

$$\sigma_{1.06} = 1.034\ \sigma_{VIS}$$

$$\sigma_{3-5} = \sigma_{VIS}[-1.070 \times 10^{3} + 1.615 \times 10^{3}\lambda - 1.011 \times 10^{3}\lambda^{2}$$
$$+ 3.364 \times 10^{2}\lambda^{3} - 6.265 \times 10^{1}\lambda^{4} + 6.193\lambda^{5} - 2.538 \times 10^{-1}\lambda^{6}]$$

$$\sigma_{8-12} = \sigma_{VIS}[1.891 \times 10^{4} - 1.156 \times 10^{4}\lambda + 2.919 \times 10^{3}\lambda^{2}$$
$$-3.915 \times 10^{2}\lambda^{3} + 2.937 \times 10^{1}\lambda^{4} - 1.169\lambda^{5} + 1.928 \times 10^{-2}\lambda^{6}]$$

These results are based upon the assumptions that the only aerosol particles in the atmosphere are spherical ice crystals and that no liquid water or other particles are present in sufficient numbers to be significant. These assumptions are probably valid for a steady state ice fog but are questionable during formation and dissipation stages. Also, other effects such as absorption of infrared radiation by carbon dioxide and water vapor and multiple scattering effects have not been included in this study.

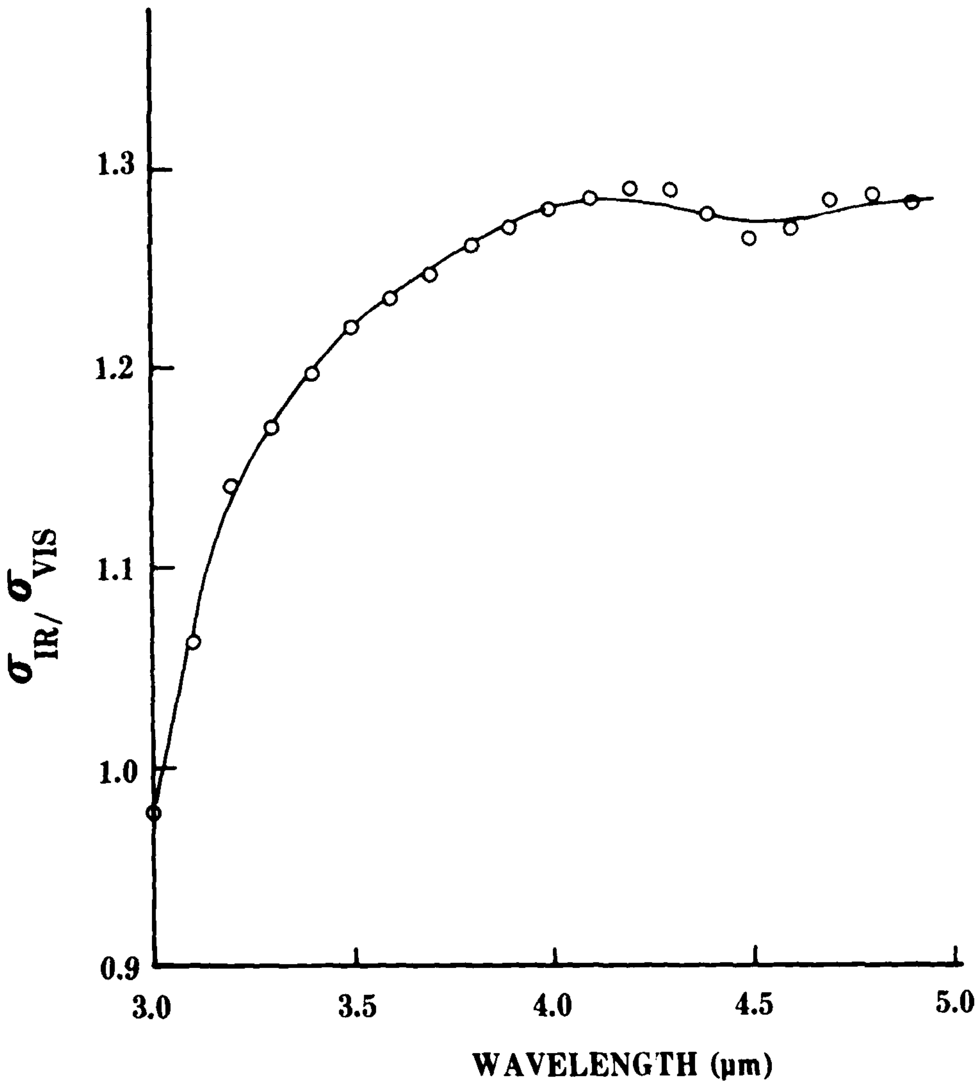

Figure 2. Ratio of infrared extinction coefficient (3 to 5 micrometers) to the visible extinction coefficient as a function of wavelengths.

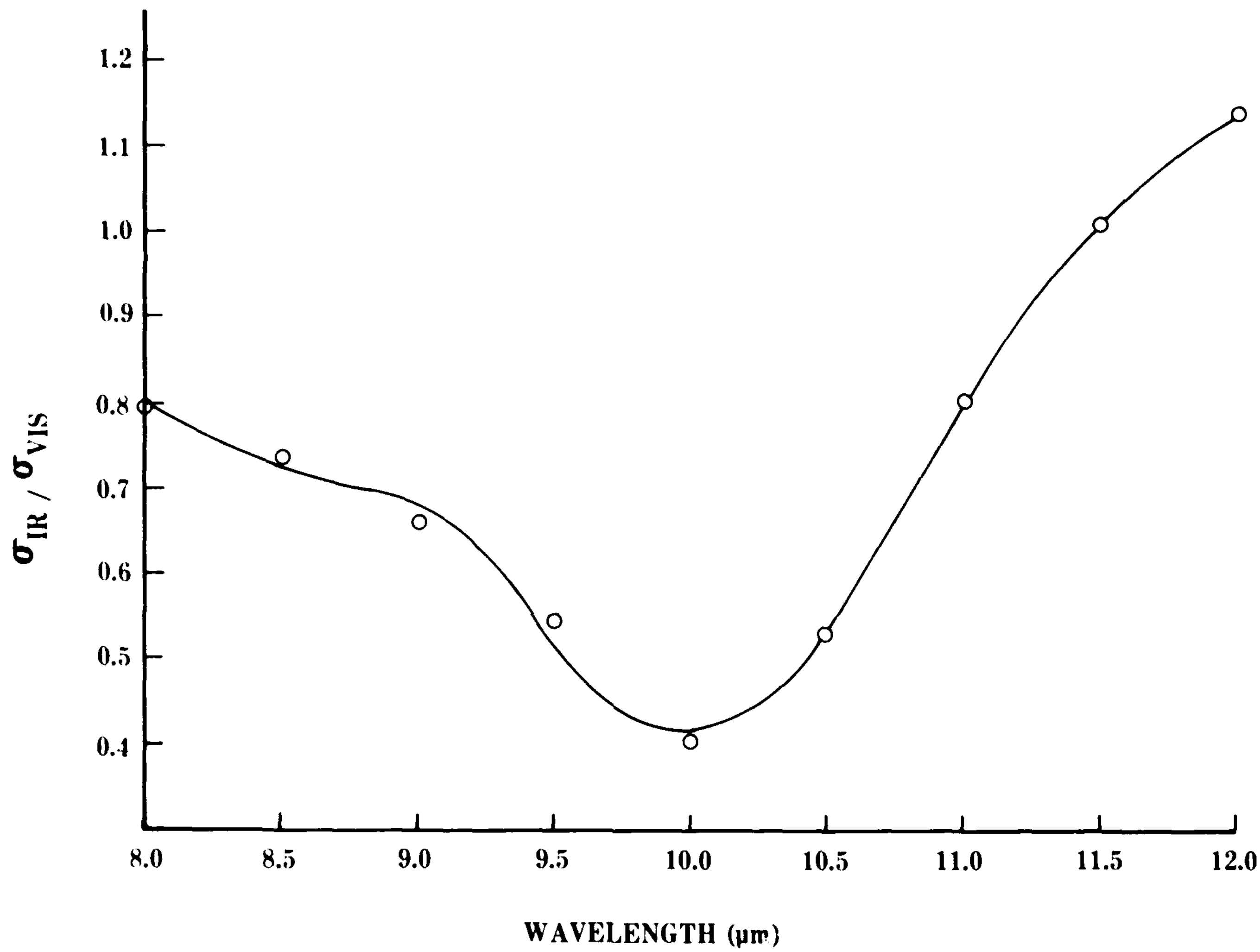

Figure 3. Ratio of infrared extinction coefficient (8 to 12 micrometers) to the visible extinction coefficient as a function of wavelength.

TABLE 2. REGRESSION EQUATION COEFFICIENTS RELATING INFRARED AND VISIBLE VOLUME EXTINCTION COEFFICIENTS FOR ICE FOG

Coefficient	3μm to 5μm	8μm to 12μm
A(0)	-1.06969×10^{3}	1.89126×10^{4}
A(1)	1.61499×10^{3}	-1.15608×10^{4}
A(2)	-1.01128×10^{3}	2.91854×10^{3}
A(3)	3.36361×10^{2}	-3.91466×10^{2}
A(4)	-6.26476×10^{1}	2.93719×10^{1}
A(5)	6.19322	-1.16888
A(6)	-2.53842×10^{-1}	1.92771×10^{-2}

$$\sigma_{IR} = \sigma_{VIS} [A(0) + A(1)\lambda + A(2)\lambda^{2} + A(3)\lambda^{3} + A(4)\lambda^{4} + A(5)\lambda^{5} + A(6)\lambda^{6}]$$

Note that the relationships stated above were derived from mean values obtained from using only two particle size distributions which may not necessarily be typical for ice fog in general. The ratio of infrared and visible extinction coefficients for the two size distributions varied by as much as 8 percent in the 3- to 5-micrometer region and 25 percent in the 8- to 12-micrometer region. Thus, the extinction coefficients obtained by use of these functions should be considered as examples and not necessarily precise for a specific ice fog event. However, the extinction coefficients for the 3- to 5-micrometer wavelengths might be expected to exhibit less variation during different ice fog conditions than the coefficients for the 8- to 12-micrometer wavelengths.

One question which frequently arises in obscuration studies is whether there is an advantage to operating at one wavelength as opposed to some other one in terms of the extent of the obscuration. Since according to the Koschmeider relationship, visual range is inversely proportional to the extinction coefficient, a larger extinction coefficient implies a greater obscuration. This study shows that visible wavelengths are less obscured in ice fog than in wavelengths at 1.06, 3.5 to 5.0, and 11.5 to 12.0 micrometers. The transmission was found to be better than the visible at wavelengths of 3.0 and 8 to 11 micrometers. Most notably, transmission at 10 micrometers was better than at visible wavelengths by a factor of two.

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